

Higgs Physics at Future Colliders: How far can we go?

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Dallas, 01/2005

1. Motivation for the Higgs
2. Higgs coupling determination at the LHC
3. Motivation for SUSY
4. The heavy SUSY Higgs mass scale
5. Conclusions

1. Motivation for the Higgs

Problem:

Gauge fields Z, W^+, W^- are **massive**

explicite mass terms in the Lagrangian \Leftrightarrow breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

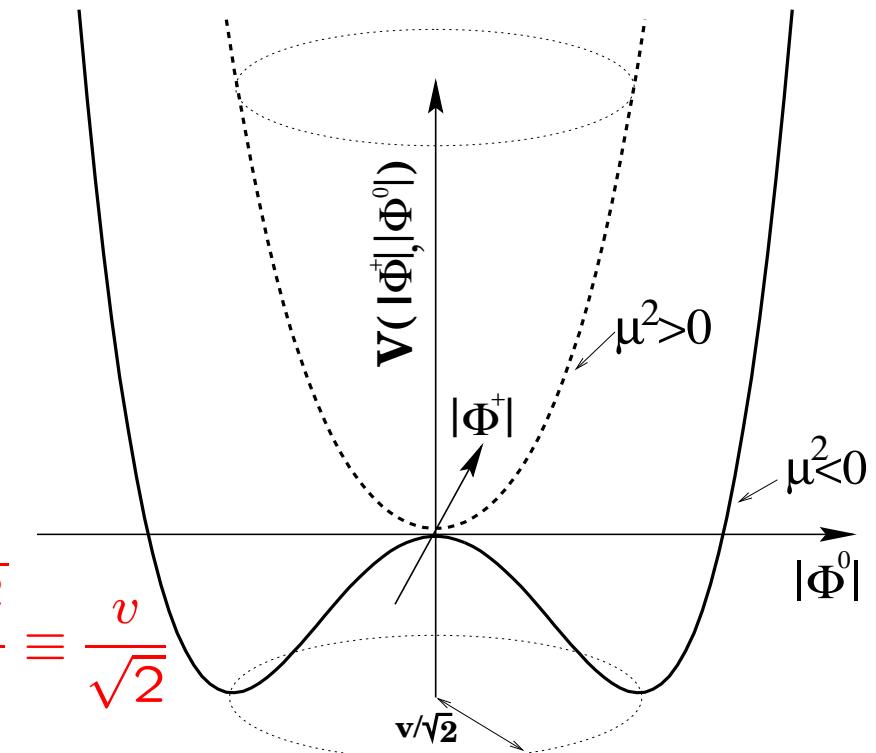
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 |\Phi^\dagger \Phi| + \lambda |\Phi^\dagger \Phi|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad (\text{unitary gauge})$$

H : elementary scalar field, Higgs boson

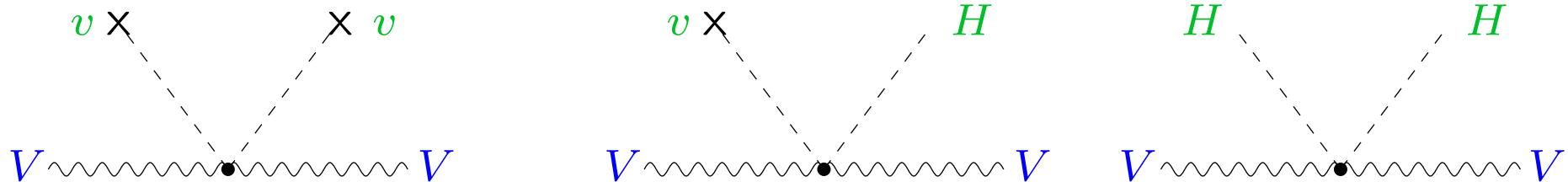
Lagrange density:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

Gauge invariant coupling to gauge fields

⇒ mass terms for gauge bosons and fermions

1.) $VV\Phi\Phi$ coupling:

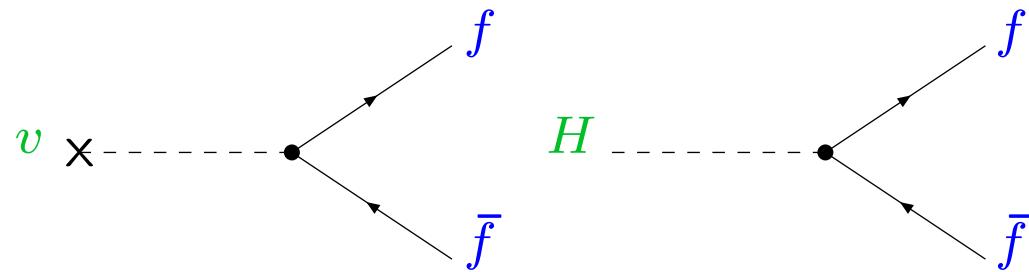


⇒ VV mass terms

$$g_2^2 v^2 / 2 \equiv M_W^2, (g_1^2 + g_2^2) v^2 / 2 \equiv M_Z^2 \Rightarrow \text{coupling} \propto \text{masses}$$

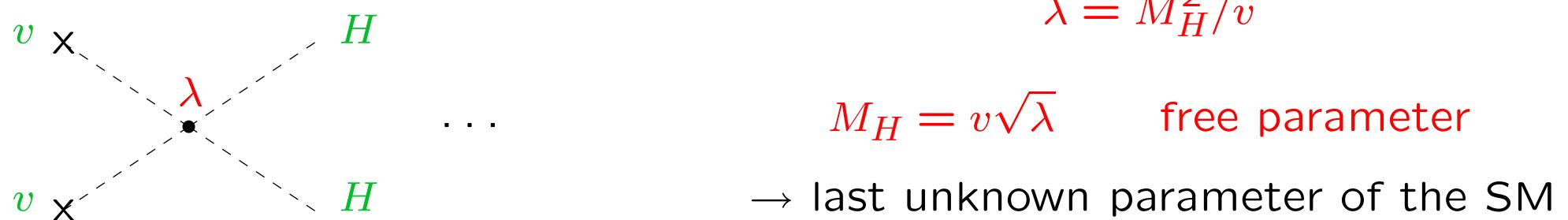
⇒ triple/quartic couplings to gauge bosons

2.) fermion mass terms: Yukawa couplings



$$m_f = v g_f \Rightarrow \text{coupling} \propto \text{masses}$$

3.) mass of the Higgs boson: self coupling



⇒ establish Higgs mechanism ≡ find the Higgs ⊕ measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \rightarrow W_L W_L$

$$\mathcal{M}_V = \text{Diagram showing two incoming } W \text{ bosons scattering into } \gamma, Z + \text{Diagram showing two incoming } W \text{ bosons scattering into } \gamma, Z + \text{Diagram showing two incoming } W \text{ bosons scattering into } W = -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$$

for $E \rightarrow \infty$

\Rightarrow violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:

$$\mathcal{M}_S = \text{Diagram showing two incoming } W \text{ bosons scattering into } H + \text{Diagram showing two incoming } W \text{ bosons scattering into } H = g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$$

for $E \rightarrow \infty$

$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4} (g_{WWH}^2 - g^2 M_W^2) + \dots$$

\Rightarrow compensation of terms with bad high-energy behavior for

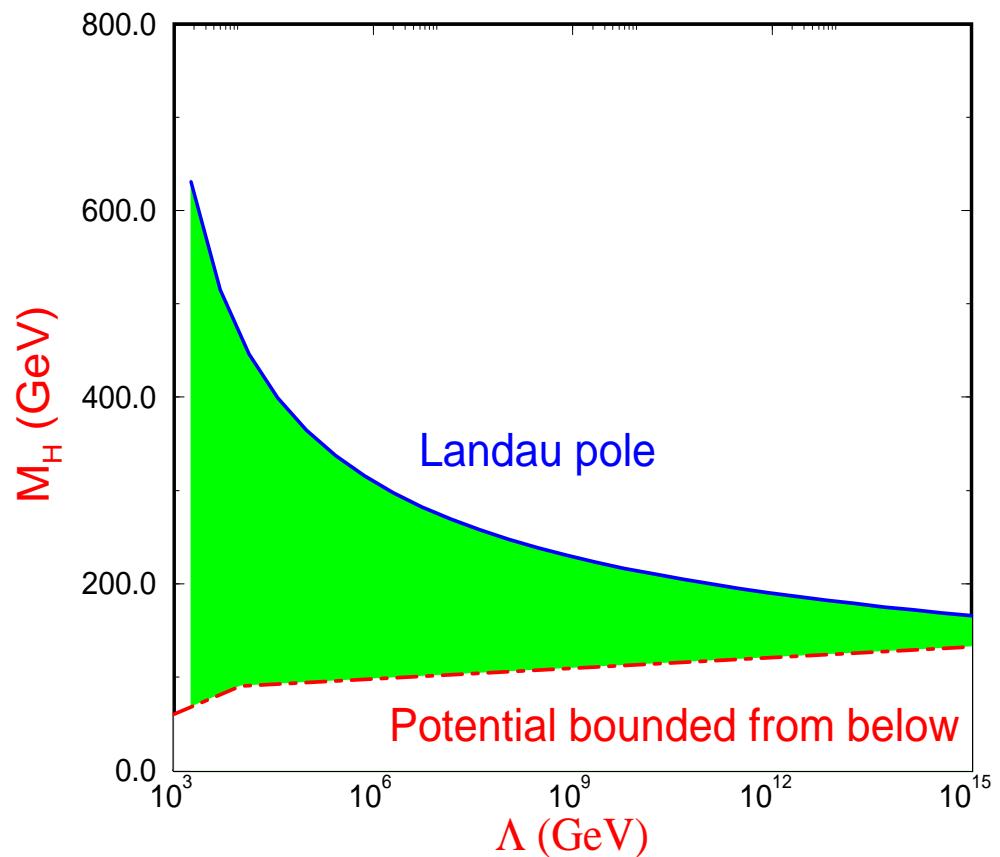
$$g_{WWH} = g M_W$$

What else do we know about the Higgs boson?

SM at high energies

- upper limit on M_H :
 - dependence of coupling λ_{HHHH} from energy scale Λ
 - ⇒ divergence: Landau pole
- lower limit on M_H :
 - stability of the vacuum :
 $V(v) < V(0)$
 - [Coleman, Weinberg '73]
- combined

⇒

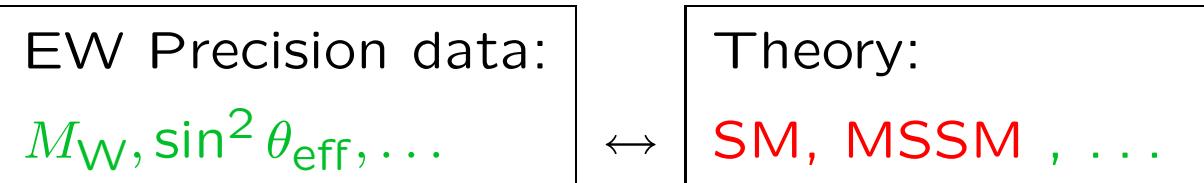


Λ : scale up to which the SM is valid

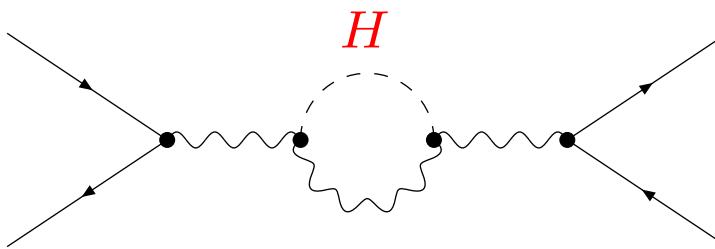
$$\Lambda = M_{\text{GUT}} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$$

Indirect measurements via precision observables (POs):

Comparison of electro-weak precision observables with theory:



Test of theory at quantum level: Sensitivity to loop corrections



All parameters of the model enter
limits on M_H

Global fit to all SM data:

[LEPEWWG '04]

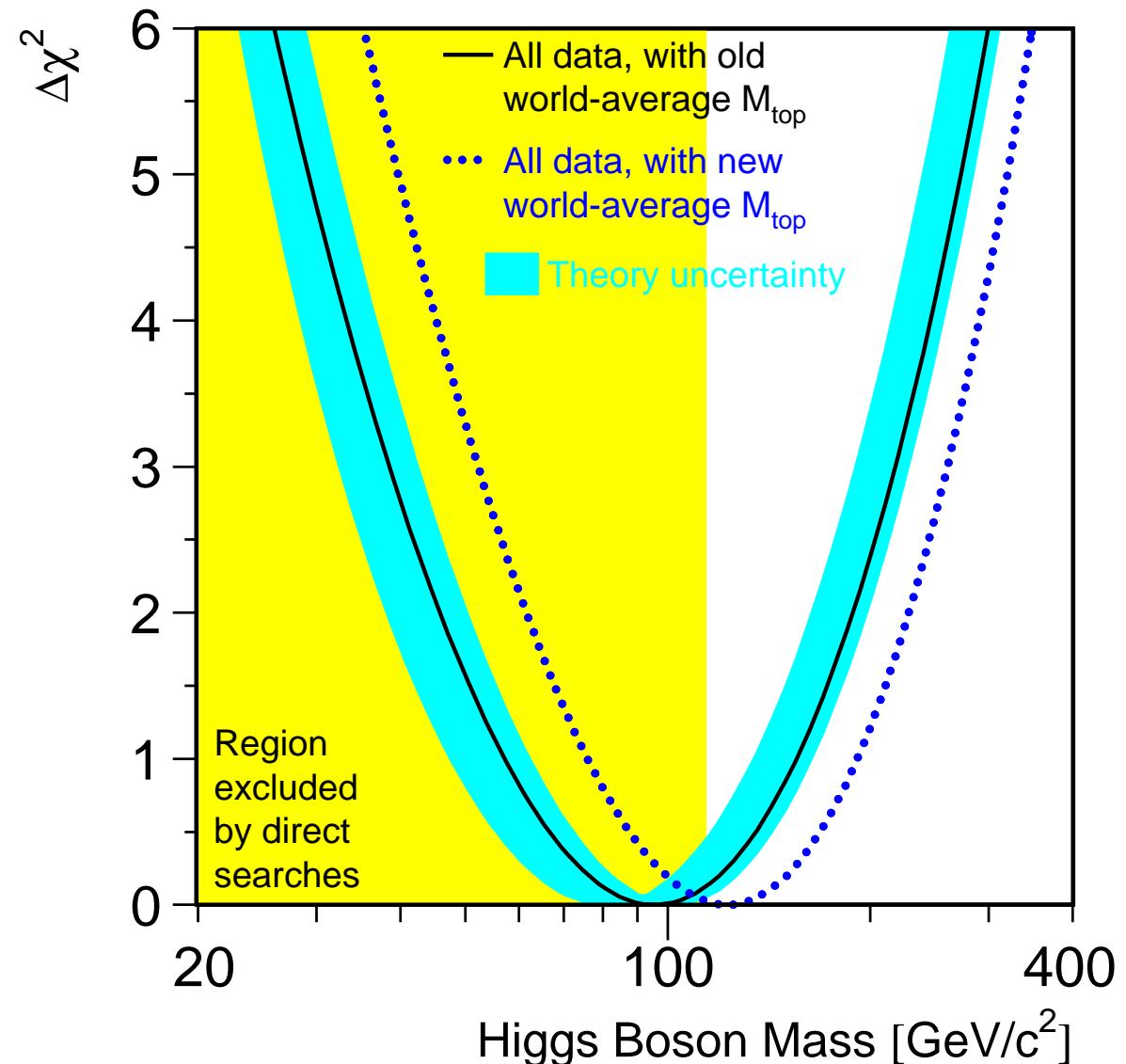
$$\Rightarrow M_H = 117^{+67}_{-45} \text{ GeV}$$

$M_H < 251$ GeV, 95% C.L.

Assumption for the fit:

SM incl. Higgs boson

\Rightarrow no confirmation of
Higgs mechanism

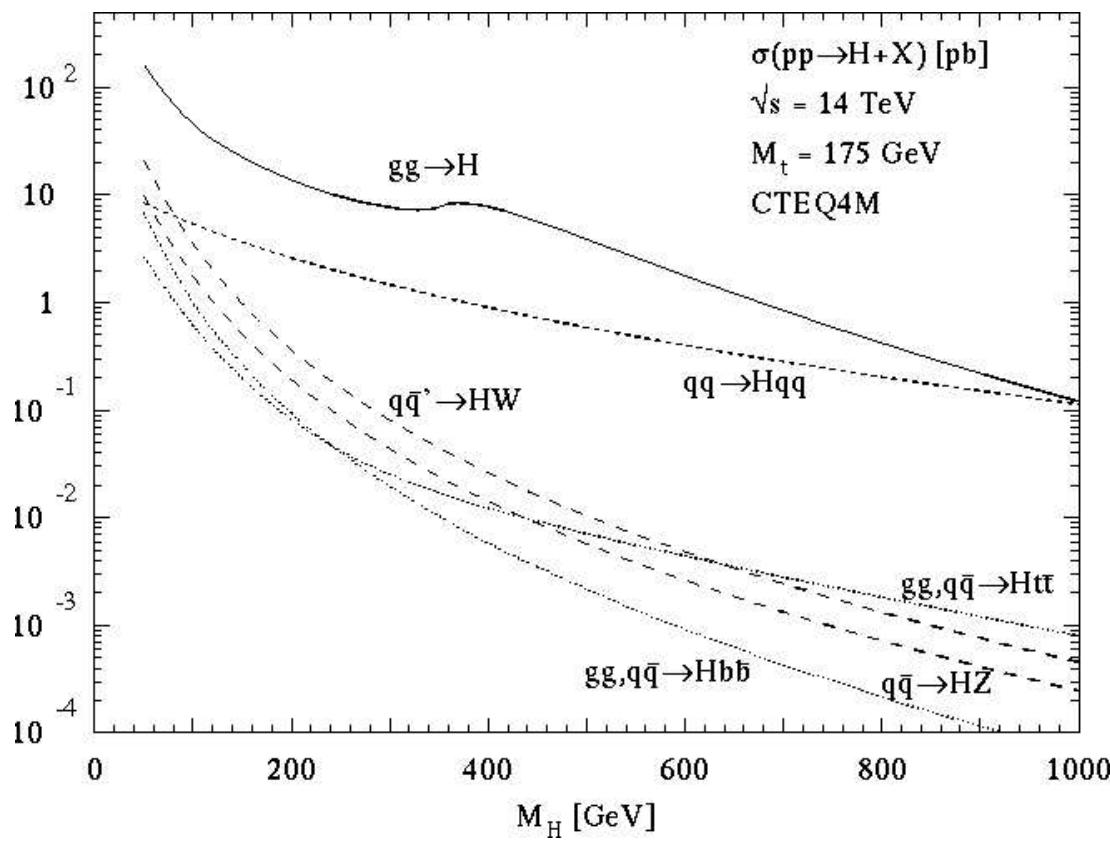


\Rightarrow Higgs boson seems to be light, $M_H \lesssim 250$ GeV

2. Higgs coupling determination at the LHC

[M. Dührssen, S.H., H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld '04]

Higgs production at the LHC:



gluon fusion: $gg \rightarrow H$

weak boson fusion (WBF):
 $q\bar{q} \rightarrow q'\bar{q}'H$

top quark associated
production: $gg, q\bar{q} \rightarrow t\bar{t}H$

weak boson associated
production: $q\bar{q}' \rightarrow WH, ZH$

Some LHC specifics:

No LHC analogue to recoil method at LEP/ILC: $e^+e^- \rightarrow ZH$, $Z \rightarrow e^+e^-$, $\mu^+\mu^-$
⇒ no total measurement of Higgs production cross section

QCD backgrounds ⇒ not all decay modes accessible, e.g. $H \rightarrow b\bar{b}$

Measurement of $\sigma \times \text{BR}$: narrow width approximation:

$$\Rightarrow \sigma(H) \times \text{BR}(H \rightarrow d_1d_2) = \frac{\sigma(H)^{\text{SM}}}{\Gamma_{\text{prod}}^{\text{SM}}} \times \frac{\Gamma_{\text{prod}} \Gamma_{\text{decay}}}{\Gamma_{\text{tot}}}$$

Observation of different channels (or upper bound from non-observation)
⇒ information on combinations of $\Gamma_b, \Gamma_\tau, \Gamma_W, \Gamma_Z, \Gamma_g, \Gamma_\gamma, Y_t^2$

⇒ Determination of ratios of partial width via global fit
[M. Dührssen '03]

⇒ Additional theoretical assumptions needed for absolute determination
of partial widths

Example for theoretical assumptions:

[D. Zeppenfeld, R. Kinnunen, A. Nikitenko, E. Richter-Was '00]

- SM ratio of $\Gamma(H \rightarrow b\bar{b})/\Gamma(H \rightarrow \tau^+\tau^-)$
- SM ratio of $\Gamma(H \rightarrow WW^*)/\Gamma(H \rightarrow ZZ^*)$
- no large unexpected decay modes

⇒ determination of couplings, but . . .

“SM in – SM out”?

⇒ questionable assumptions in many models (e.g. SUSY)

Q: Is it possible to measure couplings with “less” assumptions?

A: Yes! :-)

Strategy (I): very mild theoretical assumptions

- consider general multi-Higgs-doublet model
(w/o additional Higgs singlets)
(⇒ including e.g. MSSM)
- ⇒ HVV coupling bounded from above by SM value, $\Gamma_V \leq \Gamma_V^{\text{SM}}$, $V = W, Z$
- ⇒ upper bound on Γ_V

Observation of Higgs production

- ⇒ lower bound on production couplings
- lower bound on total width Γ_{tot}

Observation of $H \rightarrow VV^*$ in WBF

- ⇒ determines $\Gamma_V^2 / \Gamma_{\text{tot}}$
- ⇒ determines upper bound on Γ_{tot}
- ⇒ Absolute determination of Γ_{tot} and Higgs couplings via global fit
- ⇒ (nearly) model independent analysis

Strategy (II): more restrictive theoretical assumptions

→ consider more restrictive assumptions later

⇒ study possible improvements

Luminosity scenarios:

Three scenarios considered:

- $2 * 30 \text{ fb}^{-1}$: 30 fb^{-1} at each of the experiments
- $2 * 300 + 2 * 100 \text{ fb}^{-1}$: 300 fb^{-1} at each experiment, but only 100 fb^{-1} usable for WBF
(assume substantial degradation of WBF channel in high luminosity run)
- $2 * 300 \text{ fb}^{-1}$: 300 fb^{-1} at each experiment
(full luminosity usable for WBF channels)

Estimate of errors:

Statistical errors:

Assume **SM rates** for production and decay in each luminosity scenario

Systematic errors:

- 5% luminosity error
- uncertainties on reconstruction: identification of leptons: 2%
identification of photons: 2%
identification of b quarks: 3%
- forward tagging/veto jets: 5%
- error propagation for background determination from side-band analyses:
from 0.1% ($H \rightarrow \gamma\gamma$) to 5% ($H \rightarrow WW^*, H \rightarrow \tau^+\tau^-$)
- theoretical and parametric uncertainties for Higgs production:
 ggH : 20%, $t\bar{t}H$: 15%, WH, ZH : 7%, WBF: 4%
- theoretical and parametric uncertainties on Higgs decays:
1% (as a future expectation)

⇒ log likelihood function based on statistical and systematic errors

Decay channels considered:

- $H \rightarrow W^{+(*)}W^{-(*)} \rightarrow l^+l^- + p_{T,\text{miss}}$
- $H \rightarrow Z^{(*)}Z^{(*)}$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow \tau^+\tau^-$
- $t\bar{t}H, H \rightarrow b\bar{b}$

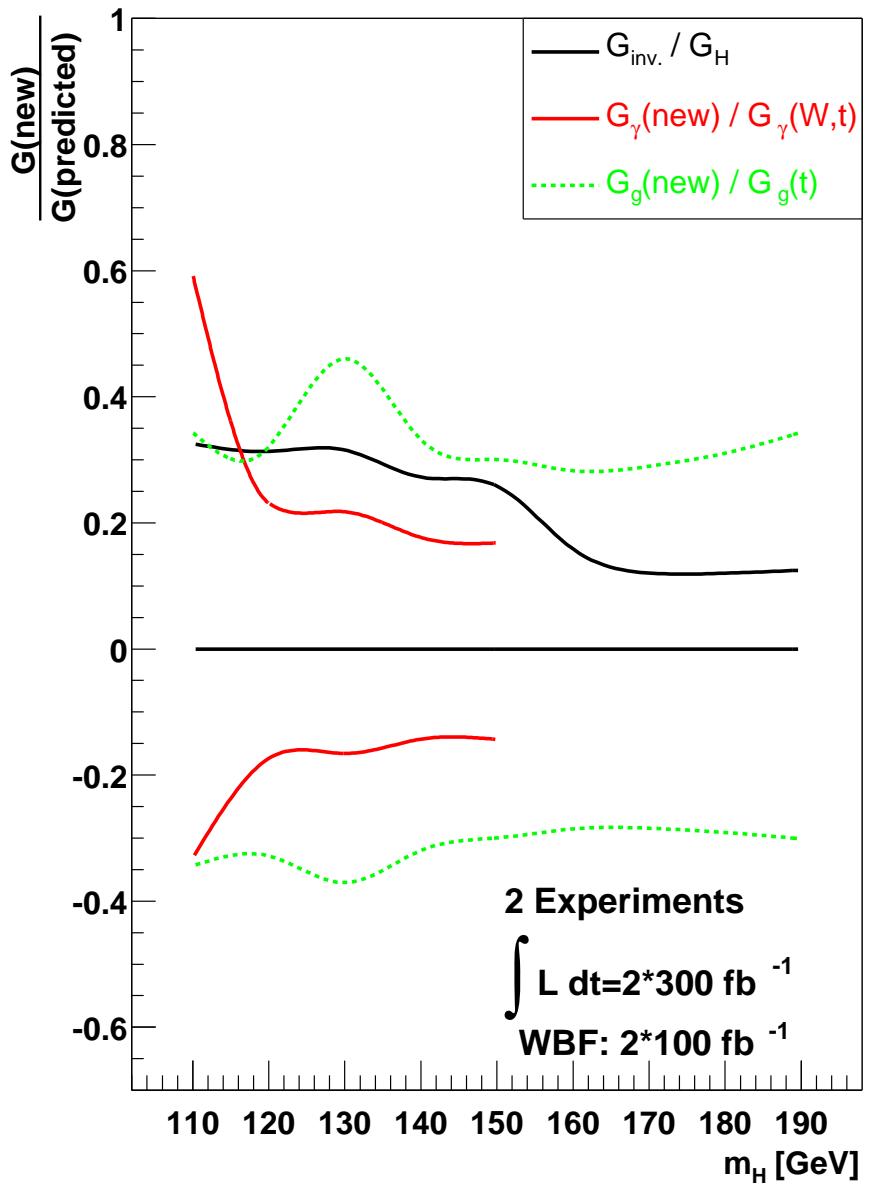
Strategy (I): assumptions (even less restrictive):

$$g_{HVV}^2 \leq 1.05 \times g_{HVV,\text{SM}}^2, \quad V = W, Z$$

5% margin to allow for

- theoretical uncertainties in translation of partial widths to g_{HVV}^2
- small admixtures of exotic states (triplets, . . .)
- Allow for additional particles contributing to $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$
(\Rightarrow fitted by pos. /neg. additional partial width to $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$)
- Allow for additional Higgs decay width
(\Rightarrow fitted by additional partial width)

Constraints on extra partial widths:



Detection of SM rates
⇒ constraints on widths:

$2 * 300 + 2 * 100 \text{ fb}^{-1}$ scenario:

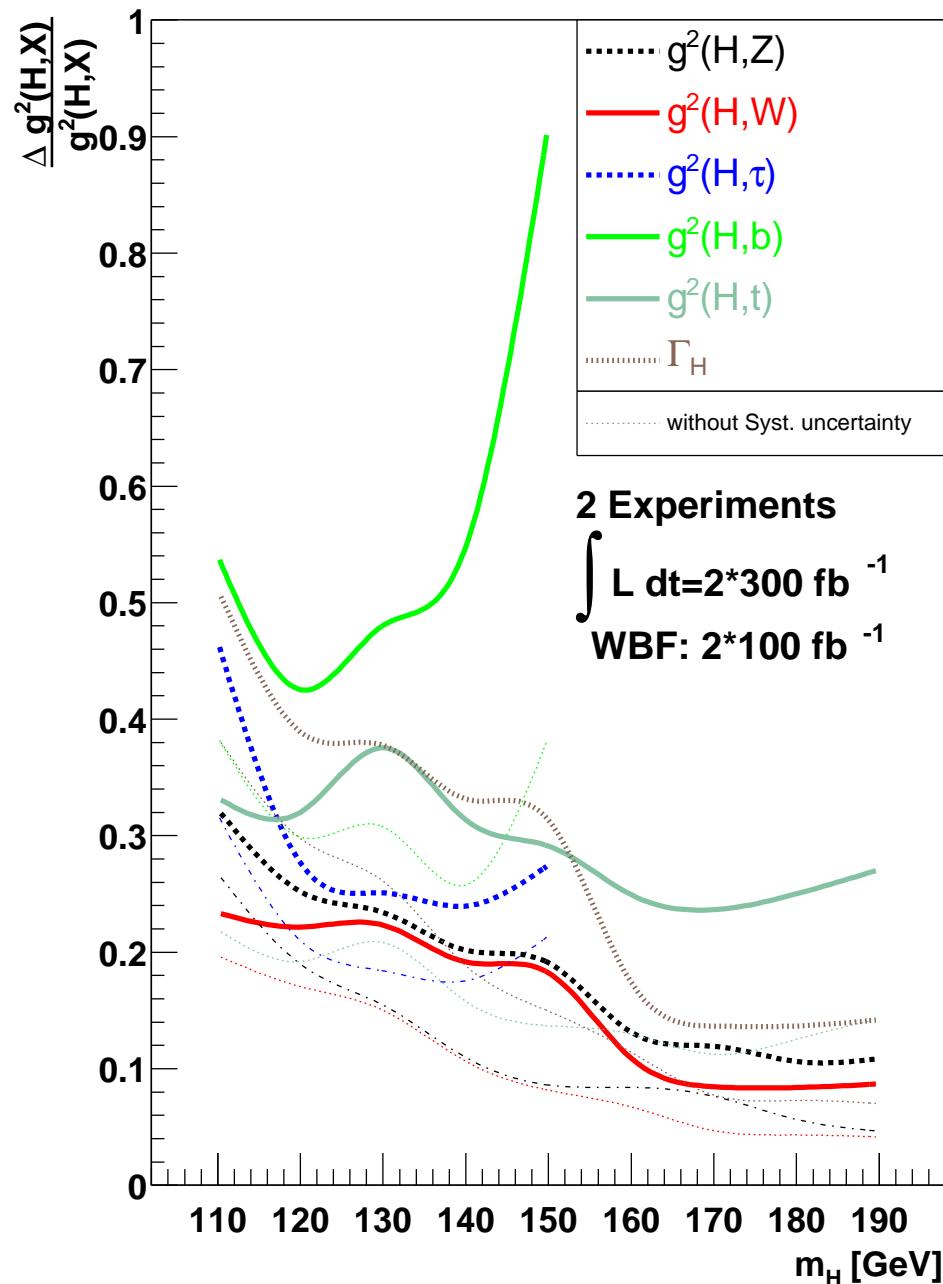
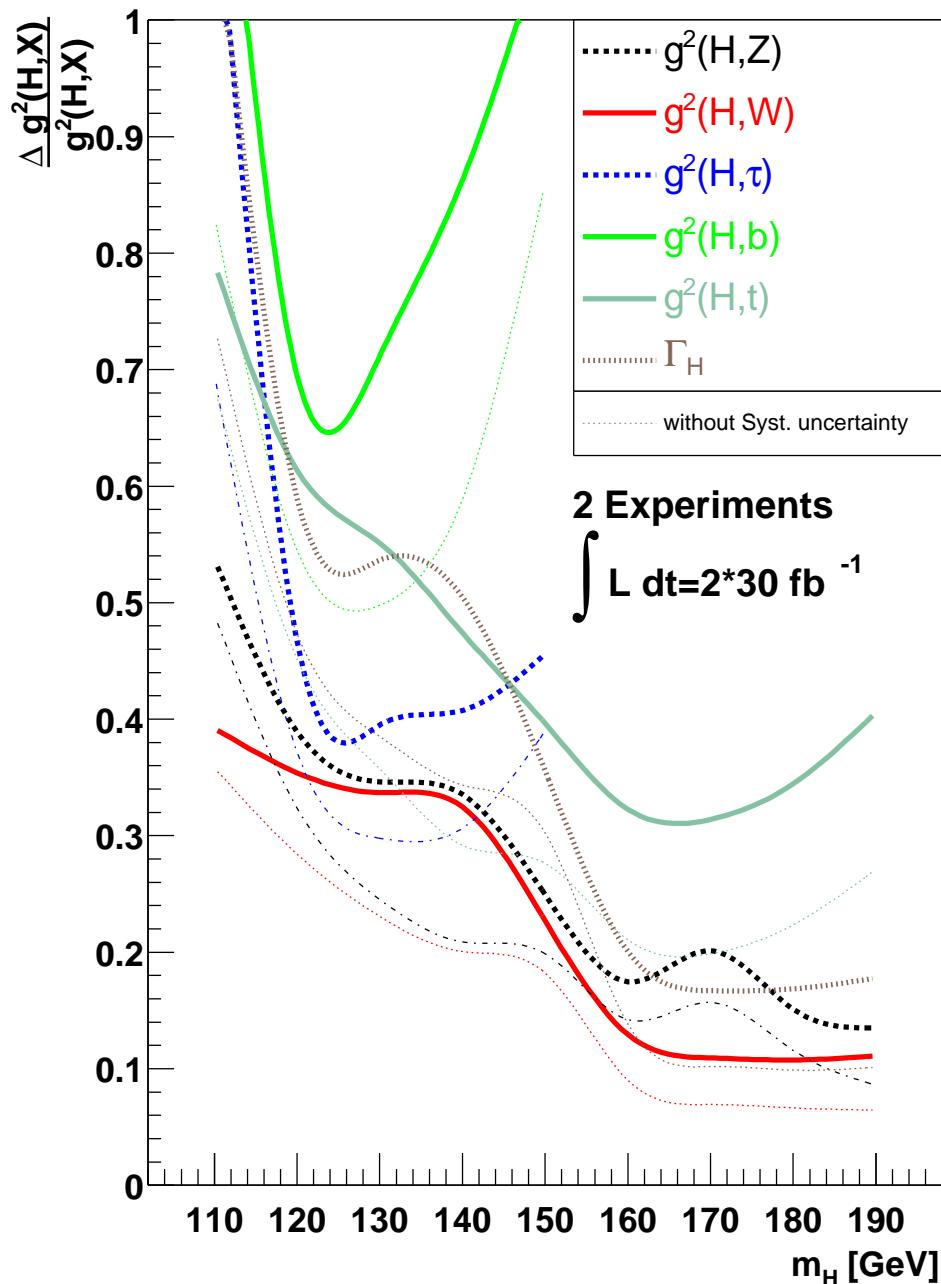
$$\Delta \Gamma_\gamma \leq 0.2 \times \Gamma_\gamma^{\text{SM}}$$

$$\Delta \Gamma_g \leq 0.4 \times \Gamma_g^{\text{SM}}$$

$$\Delta \Gamma_{\text{inv}} \leq 0.2 \times \Gamma_{\text{tot}}^{\text{SM}}$$

⇒ restrictions on new physics

Relative precisions for partial and total widths: two scenarios



Observations:

low luminosity scenario: $2 * 30 \text{ fb}^{-1}$:

for a light Higgs: results significantly worse as compared to higher luminosity scenario

high(er) luminosity scenario: $2 * 300 + 2 * 100 \text{ fb}^{-1}$:

- typical accuracies of 20-30% for $m_H \leq 150 \text{ GeV}$
- 10% accuracies for HVV couplings above WW threshold

high luminosity scenario: $2 * 300 \text{ fb}^{-1}$:

significant improvement over $2 * 300 + 2 * 100 \text{ fb}^{-1}$ only in $H\tau\tau$ coupling
(WBF crucial for $H \rightarrow \tau^+\tau^-$)

Systematic errors contribute up to half of the total error, especially at high luminosity

Strategy (II): more restrictive assumptions:

additional assumption: HWW , HZZ couplings close to their SM values:

$$g_{HWW}^2 = g_{HWW,SM}^2 \pm 5\%, \quad g_{HZZ}^2 = g_{HZZ,SM}^2 \pm 5\%$$

→ realized e.g. in the MSSM for $M_A \gtrsim 200$ GeV (decoupling regime)

Further assumption (with small impact):

no new particles in loops of $H \rightarrow \gamma\gamma$ and $gg \rightarrow H$
(i.e. couplings fixed in terms of SM couplings and particles)

Additional Higgs decays still allowed

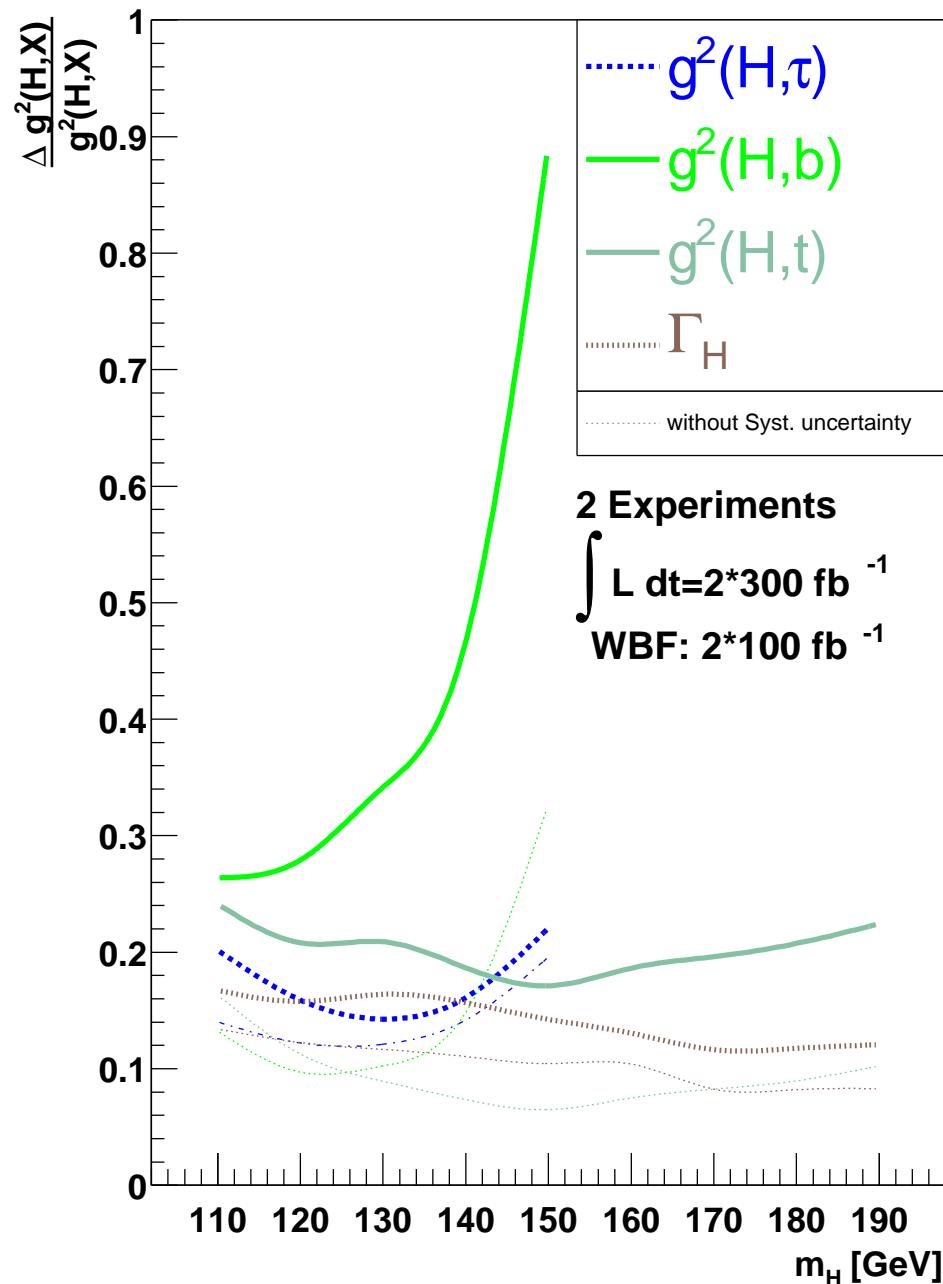
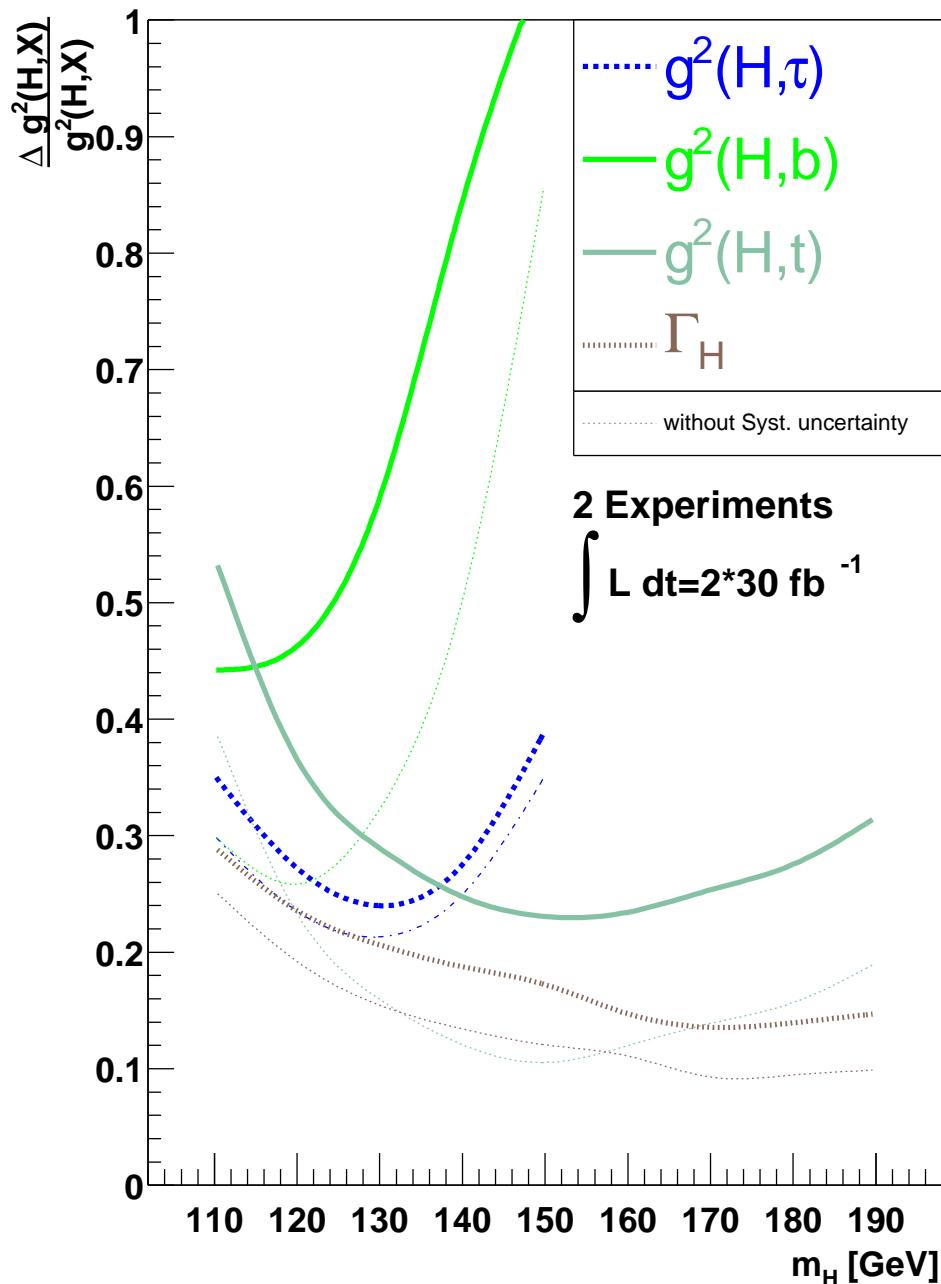
⇒ investigate improvements in width determination

→ T

⇒ drastic improvement in width determination

⇒ 10-20% precision in high luminosity scenario

Relative precisions for partial and total widths:



3. Motivation for SUSY

Supersymmetry (SUSY) : Symmetry between

Bosons \leftrightarrow Fermions

$$Q \mid \text{Fermion} \rangle \rightarrow \mid \text{Boson} \rangle$$

$$Q \mid \text{Boson} \rangle \rightarrow \mid \text{Fermion} \rangle$$

Simplified examples:

$$Q \mid \text{top, } t \rangle \rightarrow \mid \text{scalar top, } \tilde{t} \rangle$$

$$Q \mid \text{gluon, } g \rangle \rightarrow \mid \text{gluino, } \tilde{g} \rangle$$

\Rightarrow each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}}$ \Rightarrow SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian

SUSY particles are made heavy: $M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})$

Supersymmetry: Motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

→ more than 9 reasons as a motivation:
(incl. 3 1/2 exp. verified SUSY predictions!)

1.) (Original motivation:) Stability of Higgs mass against higher order corrections in the MSSM

$$\Rightarrow M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})$$

2.) Haag-Lopuszanski-Sohnius theorem:
maximal gauge symmetry for a QFT:
inner gauge symmetry \otimes (local) Susy

3.) Lorentz algebra \subset Susy algebra (local)
→ connection to general relativity
Superstring theories contain $N = 1$ Susy as low energy limit.

4.) Unification of gauge couplings:

Not possible in the SM, but in the **MSSM** (although it was **not** designed for it.)

$$\Rightarrow M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})$$

5.) Lifetime of the proton: for SU(5) GUTs:

$$\tau_{p,\text{SM}} < \tau_{p,\text{exp}} < \tau_{p,\text{SUSY}}$$

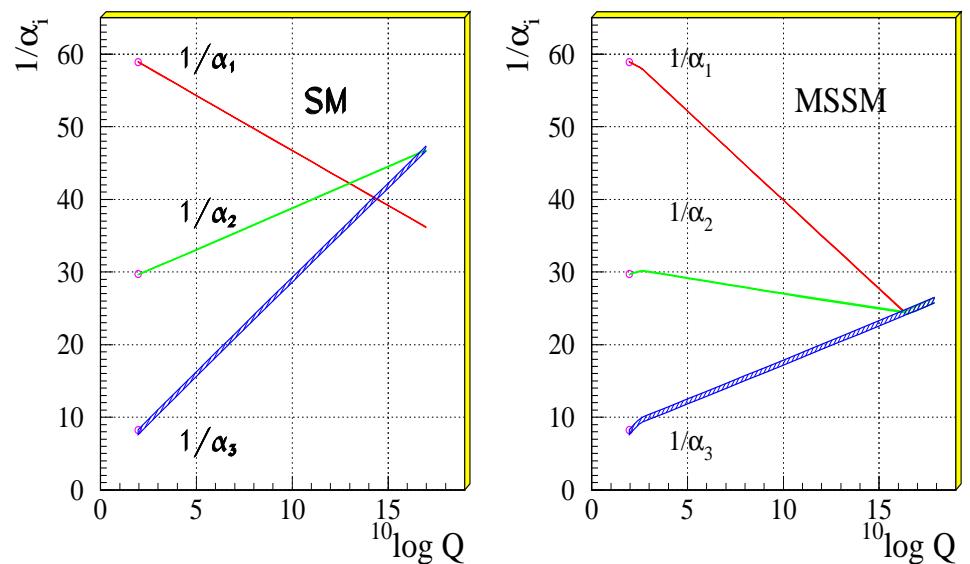
6.) Spontaneous symmetry breaking via Higgs mechanism is automatically achieved in **SUSY GUTs**

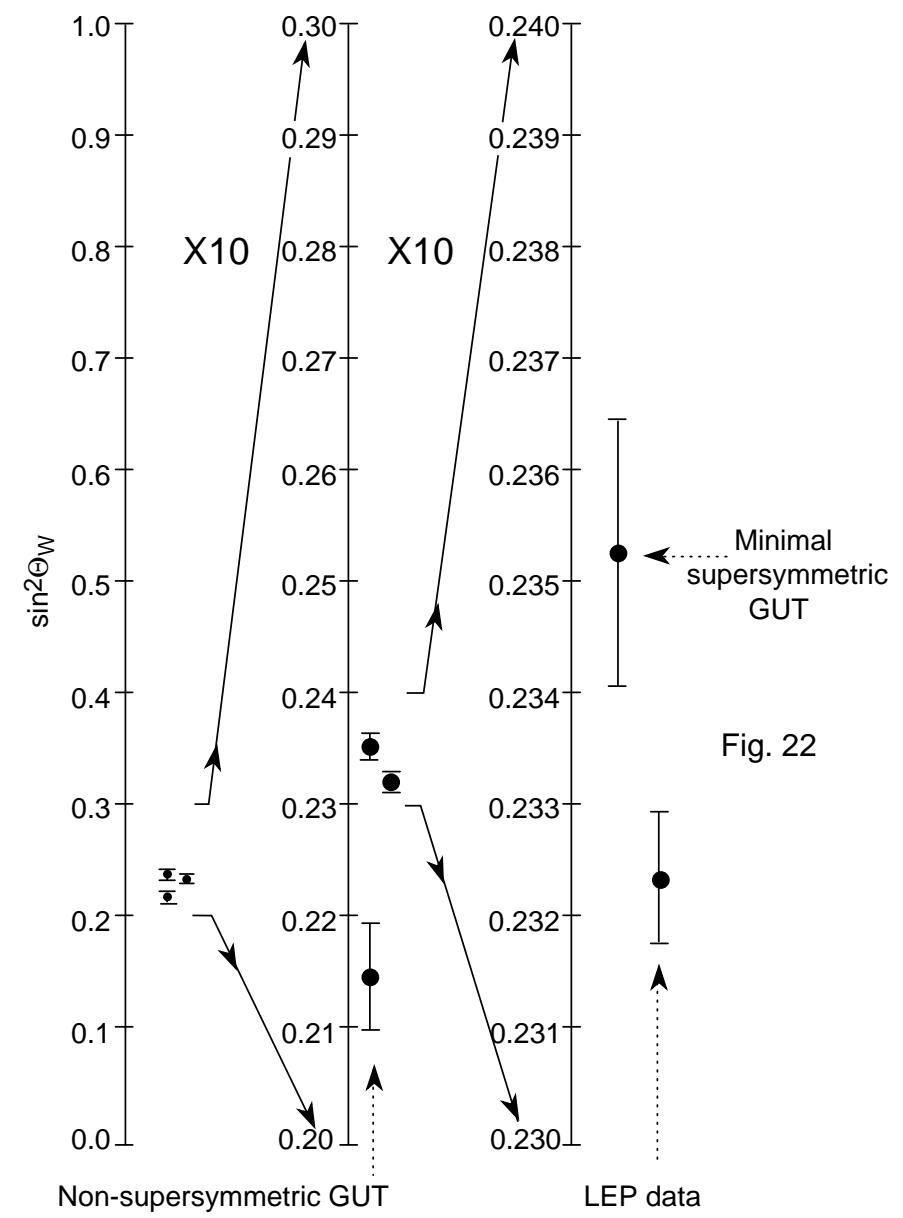
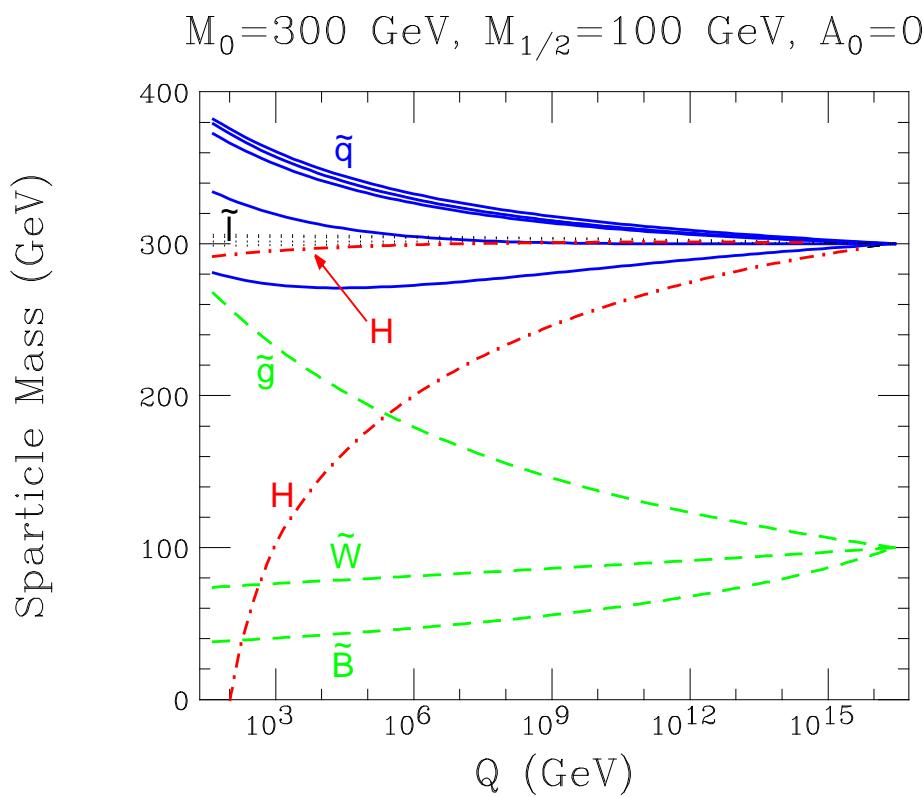
$\rightarrow T$

SUSY prediction #1
experimentally verified:

$$m_t = 150 - 200 \text{ GeV}$$

Unification of the Coupling Constants in the SM and the minimal MSSM





7.) Prediction for $\sin \theta_W | M_{GUT} = \frac{3}{8}$
low energy prediction via RGE $\rightarrow T$

SUSY prediction #2 exp. verified:
 $\sin^2 \theta_{\text{eff}} \approx 0.232$

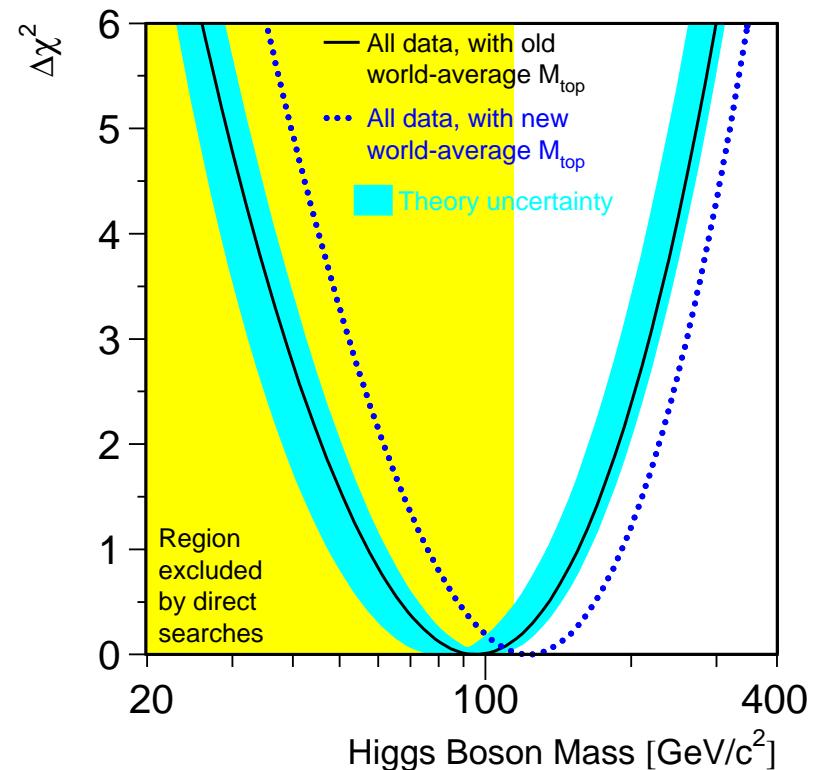
8.) LSP (lightest SUSY particle) is stable

SUSY prediction #3 exp. verified:
cold dark matter
(with correct properties)

9.) Prediction of a light Higgs boson in the
MSSM (see below): $m_h \lesssim 140 \text{ GeV}$

Indirect search: Global fit to SM data:
[LEPEWWG '04]

SUSY prediction #4 exp. verified:
 $m_h \lesssim 140 \text{ GeV}$



...) Solution for Flavor problem? Solution for Baryogenesis?

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$[u, d, c, s, t, b]_{L,R}$	$[e, \mu, \tau]_{L,R}$	$[\nu_{e,\mu,\tau}]_L$	Spin $\frac{1}{2}$
$[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R}$	$[\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R}$	$[\tilde{\nu}_{e,\mu,\tau}]_L$	Spin 0
g	$\underbrace{W^\pm, \textcolor{red}{H}^\pm}_{\textcolor{blue}{H}_1^0, H_2^0}$	$\gamma, Z, \underbrace{H_1^0, H_2^0}_{\tilde{\chi}_{1,2}^0, \tilde{\chi}_{1,2,3,4}^0}$	Spin 1 / Spin 0
\tilde{g}	$\tilde{\chi}_{1,2}^\pm$	$\tilde{\chi}_{1,2,3,4}^0$	Spin $\frac{1}{2}$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: h^0, H^0, A^0, H^\pm

Goldstone bosons: G^0, G^\pm

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2(\tan \beta + \cot \beta)$$

Contrary to the SM:

m_h is not a free parameter

MSSM tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta m_h^2 \sim G_\mu m_t^4 \ln \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Measurement of m_h , Higgs couplings \Rightarrow test of the theory

LHC: $\Delta m_h \approx 0.2$ GeV

ILC: $\Delta m_h \approx 0.05$ GeV

$\Rightarrow m_h$ will be (the best?) electroweak precision observable

Upper bound on m_h in the MSSM:

“Unconstrained MSSM”:

M_A , $\tan \beta$, 5 parameters in \tilde{t} – \tilde{b} sector, μ , $m_{\tilde{g}}$, M_2

$$m_h \lesssim 140 \text{ GeV}$$

for $m_t = 178 \text{ GeV}$

(including theoretical uncertainties from unknown higher orders)
⇒ observable at the LHC

Obtained with:

FeynHiggs

[S.H., W. Hollik, G. Weiglein '98, '00, '02]

[T. Hahn, S.H., W. Hollik, G. Weiglein '03, '04]

www.feynhiggs.de

→ all Higgs masses, couplings, BRs (easy to link, easy to use :-)

4. The heavy SUSY Higgs mass scale

LHC/ILC reach for MSSM Higgs bosons:

LHC:

h : all $M_A - \tan \beta$ plane

H, A : unreachable parts

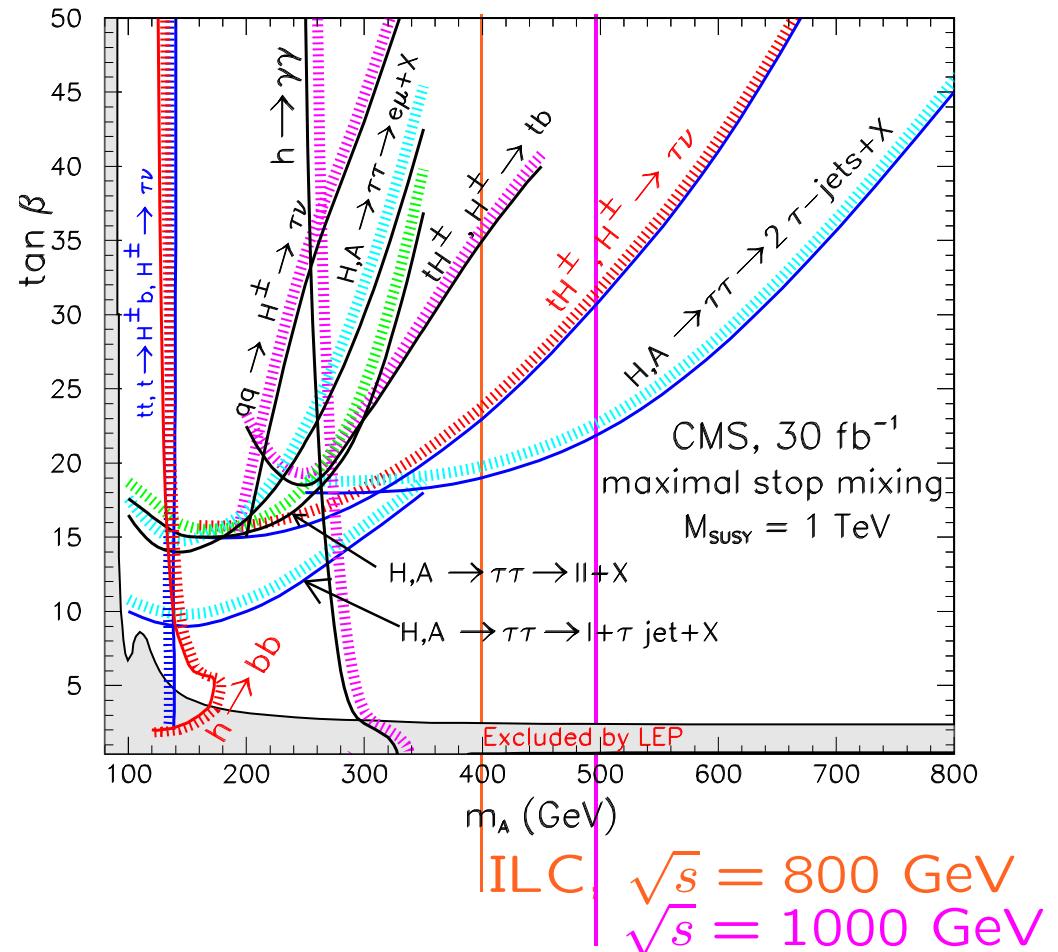
CMS, 30 fb^{-1} , m_h^{\max} scenario: \Rightarrow

ILC:

kinematic limit: $M_A \lesssim \sqrt{s}/2 \rightarrow T$

$\rightarrow \sqrt{s} = 800 \text{ GeV}$

$\rightarrow \sqrt{s} = 1000 \text{ GeV}$

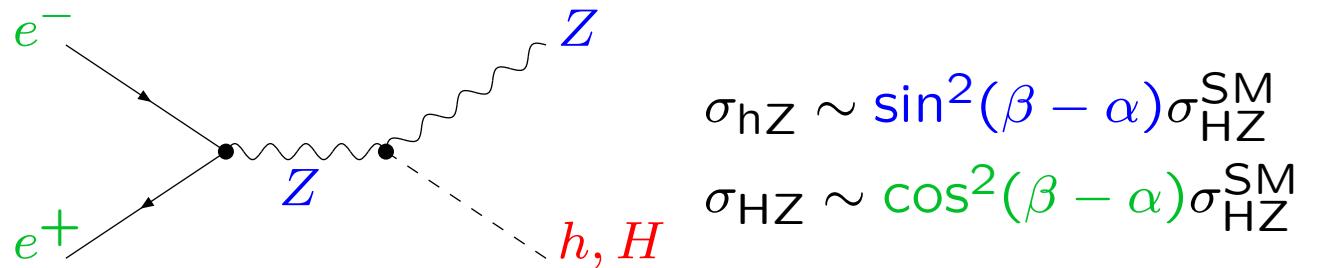


Q: Is it possible to extend the reach for heavy Higgs bosons ?

A: Yes, by direct and indirect measurements

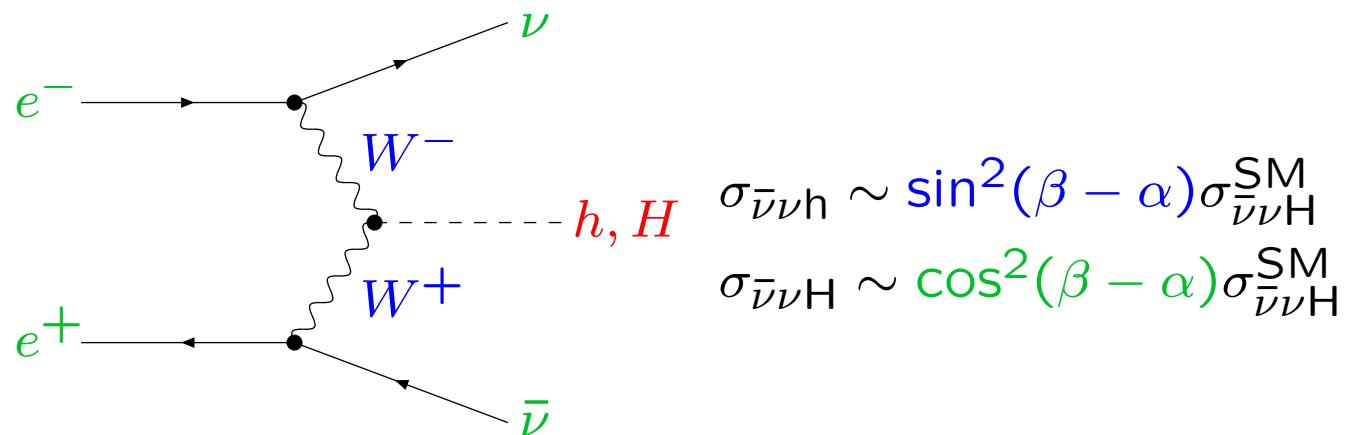
Higgs production at the ILC:

Higgs-strahlung process, $e^+e^- \rightarrow Zh, ZH$



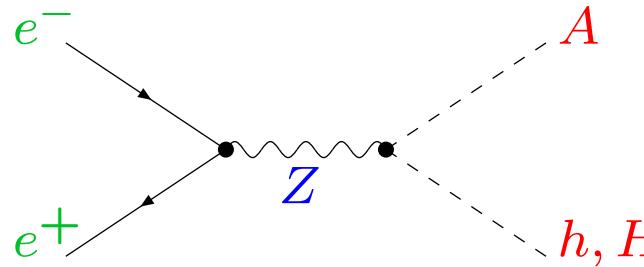
Dominates at low energies

Vector-boson fusion process, $e^+e^- \rightarrow \bar{\nu}_e \nu_e \{h, H\}$



Dominates at high energies

Higgs boson pair production, $e^+e^- \rightarrow Ah, AH$



$$\sigma_{hA} \sim \cos^2(\beta - \alpha) \sigma_{HZ}^{\text{SM}}$$
$$\sigma_{HA} \sim \sin^2(\beta - \alpha) \sigma_{HZ}^{\text{SM}}$$

Decoupling limit:

$M_A \gg M_Z$ (reached already for $M_A \gtrsim 200$ GeV)

$$\sin^2(\beta - \alpha) \rightarrow 1, \quad \cos^2(\beta - \alpha) \rightarrow 0, \quad M_H \approx M_A$$

⇒ h couples to vector bosons with SM strength

H decouples from vector bosons

production of heavy neutral Higgs bosons in e^+e^- mode only via HA pair production

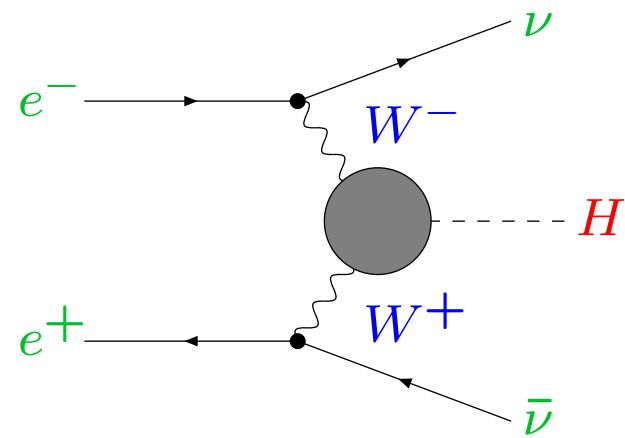
kinematical limit: $M_H, M_A \lesssim \sqrt{s}/2$

Access to the heavy SUSY Higgs at the ILC via direct production?

[T. Hahn, S.H., G. Weiglein '03]

WW fusion: $e^+e^- \rightarrow \bar{\nu}\nu H \sim \cos^2(\beta - \alpha) \Rightarrow$ decoupling

Loop corrections to VVH vertex could modify decoupling behavior:



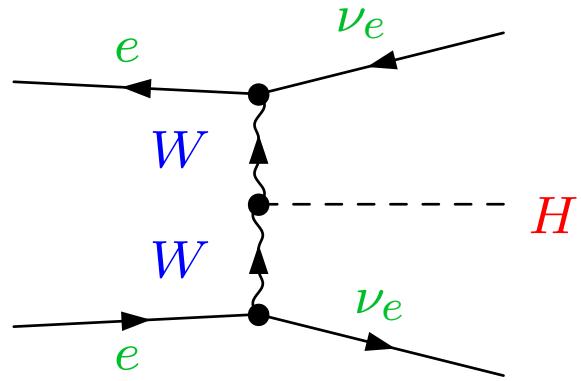
\Rightarrow Enhancement of ILC reach into region $M_H > \sqrt{s}/2$?

Existing higher order calculations:

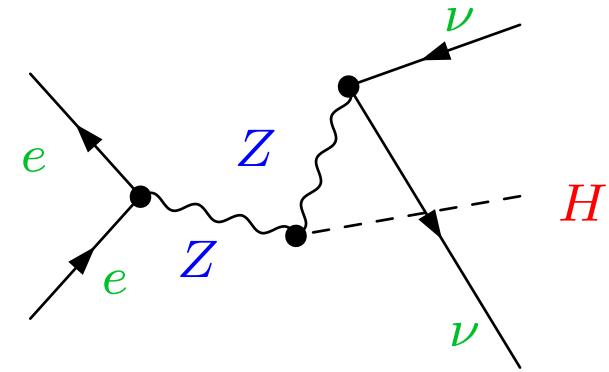
- $e^+e^- \rightarrow Zh, ZH$: large radiative corrections, up to two-loop
[S.H., W. Hollik, J. Rosiek, G. Weiglein '01]
- $e^+e^- \rightarrow Ah, AH$: large radiative corrections, up to two-loop
[S.H., W. Hollik, J. Rosiek, G. Weiglein '01]
- $e^+e^- \rightarrow \bar{\nu}\nu h$, $e^+e^- \rightarrow \bar{\nu}\nu H$ (with $M_H \sim M_Z$):
[H. Eberl, W. Majerotto, V. Spanos '02]
(3. family // α_{eff} for Higgs renormalization //
“inconvenient” renormalization scheme)
- $e^+e^- \rightarrow \bar{\nu}\nu A$: no WWA tree-level coupling, one-loop result tiny
[A. Arhrib '02]
- $e^+e^- \rightarrow \nu e^\mp H^\pm$:
no $W^\mp\{\gamma, Z\}H^\pm$ tree-level coupling, one-loop result tiny
[O. Brein, T. Hahn, S.H., G. Weiglein '04]
- $e^+e^- \rightarrow \bar{\nu}\nu H_{\text{SM}}$: full $\mathcal{O}(\alpha)$ corrections
[G. Belanger et al. '02] [A. Denner, S. Dittmaier, M. Roth, M. Weber '02]
[F. Jegerlehner, O. Tarasov '02]

Some details about the calculation:

Main process: WW fusion



same final state: Higgs-strahlung

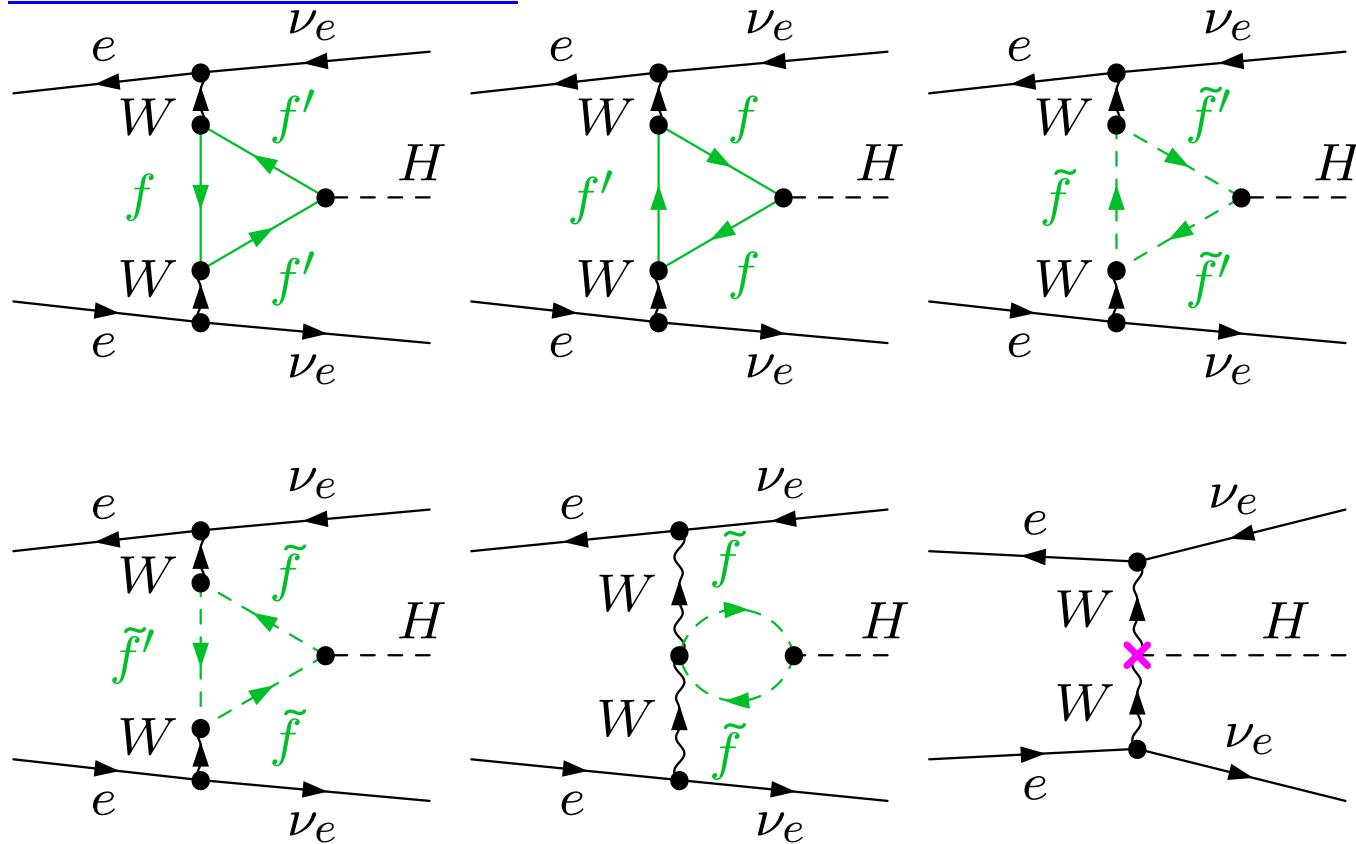


- ⇒ describe corrections to WW fusion
- ⇒ loop corrections to Higgs-strahlung taken into account in the same way

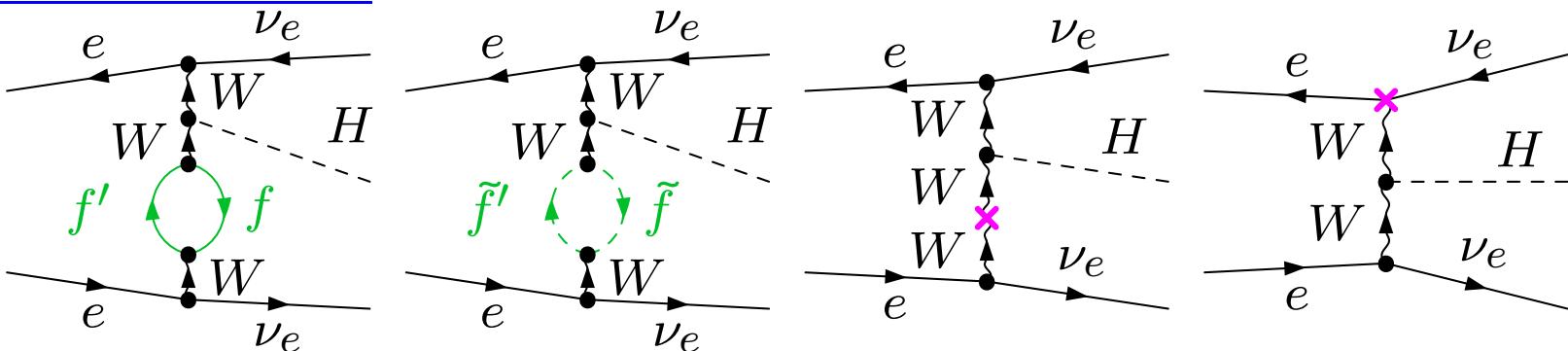
Included higher order corrections:

- ⇒ include all (s)fermion loops
- ⇒ sufficient for decoupling, other corr. suppressed by $\cos^2(\beta - \alpha)$ (mostly)

Vertex corrections:



Further diagrams:



On-shell properties of outgoing Higgs boson:

→ finite wave function renormalization

$$\Gamma_{WWH}^{0,\text{WF}} = \sqrt{\hat{Z}_H} \left(\Gamma_{HWW}^{(0)} + \frac{1}{2} \hat{Z}_{hH} \Gamma_{hWW}^{(0)} \right)$$

\hat{Z}_h, \hat{Z}_H : finite residue of Higgs propagators

$\hat{Z}_{hH}, \hat{Z}_{Hh}$: finite Higgs mixing contribution

large Higgs propagator corrections enter \Rightarrow all available used \Rightarrow FeynHiggs

α_{eff} approx. \Rightarrow outgoing Higgs boson no longer on-shell

Cross section evaluation:

amplitude for $e^+e^- \rightarrow \nu_e \bar{\nu}_e H$: $\mathcal{M}_{H,e}^{(i)}$ ($i = 0, 1$)

WW fusion + Higgs-strahlung: tree-level (incl. WF corr.) + one-loop

amplitude for $e^+e^- \rightarrow \nu_f \bar{\nu}_f H$: $\mathcal{M}_{H,f}^{(0)}$ ($f = \mu, \tau$)

(experimentally indistinguishable final state)

$$\Rightarrow \sigma_H^1 \propto |\mathcal{M}_{H,e}^{(0)} + \mathcal{M}_{H,e}^{(1)}|^2 + |\mathcal{M}_{H,\mu}^{(0)}|^2 + |\mathcal{M}_{H,\tau}^{(0)}|^2$$

Numerical analysis for $e^+e^- \rightarrow \bar{\nu}\nu H$:

Assume $\sqrt{s} = 1$ TeV

⇒ investigate whether H can be produced beyond kinematical limit
for HA pair production

Optimistic (theorists') assumptions: integrated luminosity of $\mathcal{O}(2 \text{ ab}^{-1})$

⇒ $\sigma \approx 0.01 \text{ fb}$ taken as lower limit for observability (~ 20 events)

Discuss below results with and without beam polarization :

Idealized case: 100% pol. of both beams ⇒ enhancement by factor ≈ 4

More realistic case: 80% pol. of e^- beam, 60% pol. of e^+ beam

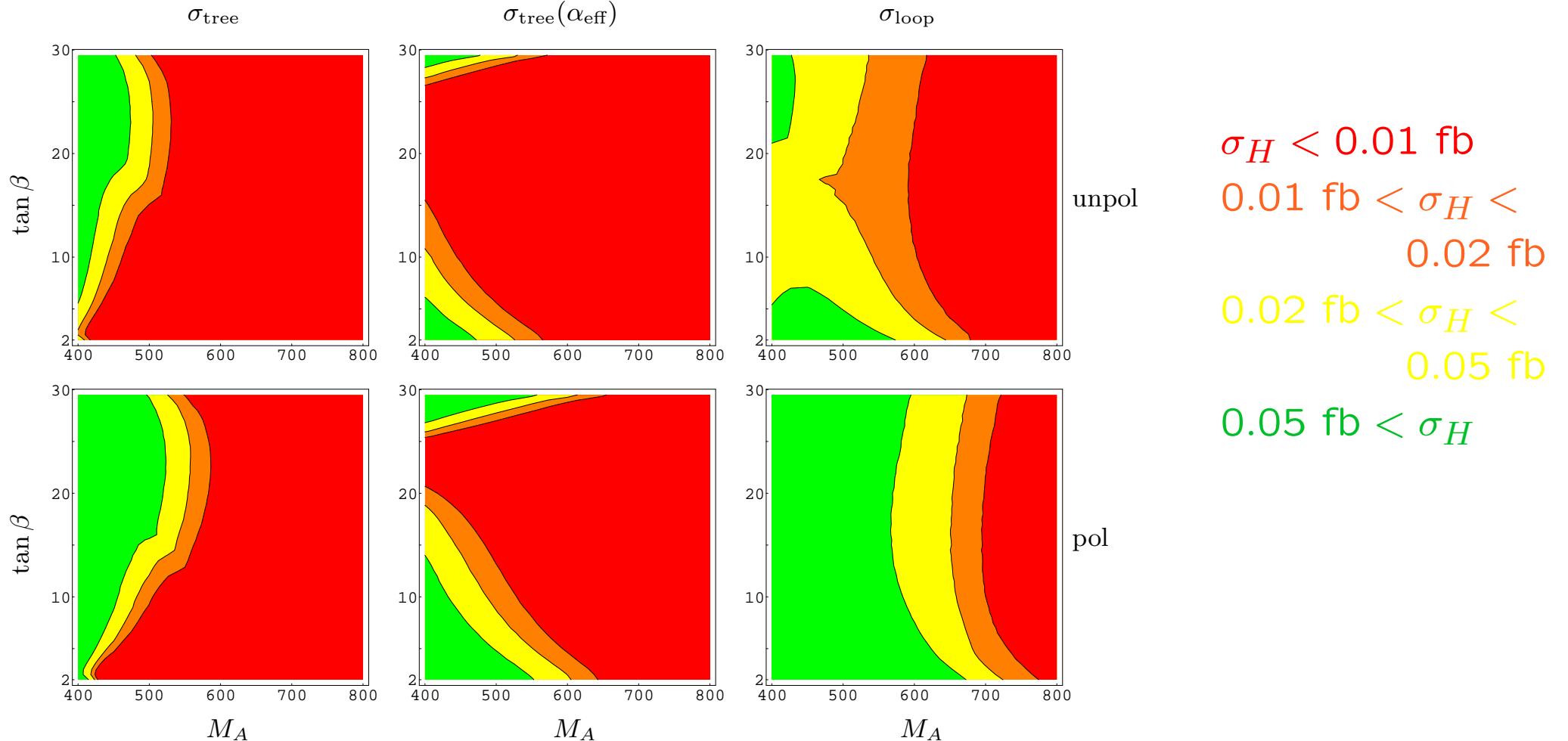
⇒ enhancement by factor ≈ 3

In examples below with beam polarization: idealized case assumed

Scenario: m_h^{\max} scenario, but $M_{\text{SUSY}} = 350 \text{ GeV}$, $\mu = 1000 \text{ GeV}$,

⇒ “ $m_h^{\max}(350/1000)$ ” scenario

Results in $m_h^{\max}(350/1000)$ scenario:



⇒ Large effects from genuine one-loop corr. and full wave function corr.

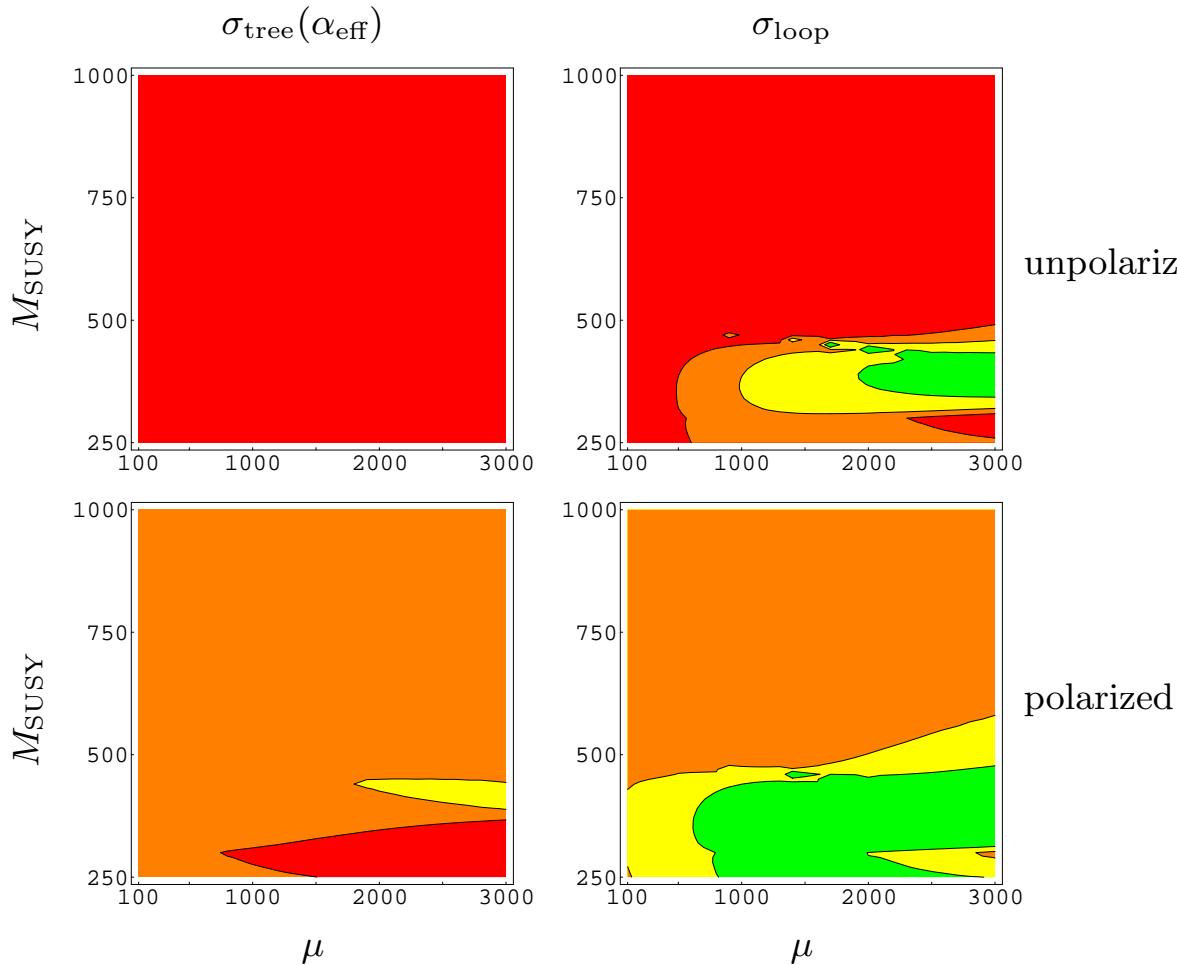
unpolarized case: H observation up to $M_A \lesssim 600 \text{ GeV}$ for all $\tan \beta$

polarized case: H observation up to $M_A = 700 - 750 \text{ GeV}$ for all $\tan \beta$

⇒ Enhancement of ILC reach by more than 200 GeV

Enhancement happens over considerable regions of MSSM parameter space

m_h^{\max} scenario, $M_A = 600$ GeV, $\tan \beta = 4$, scan over μ , M_{SUSY}



Unpolarized case:

observation possible for
nearly all $M_{\text{SUSY}} \lesssim 500$ GeV
if $\mu \gtrsim 500$ GeV

Loop corrections very
important

Polarized case:

observation possible for all
scanned values of μ and
 M_{SUSY}

5. Conclusions

- The Higgs is an essential ingredient of the SM and extensions
- Higgs coupling determination at the LHC:
 - coupling determination necessary to establish the Higgs mechanism
 - (nearly) model independent analysis
 - ⇒ coupling determination down to 20-40%
 - assume SM couplings for HWW , HZZ
 - ⇒ coupling determination down to 10-20%
- SUSY is a well motivated extension of the SM
- M_A is a crucial MSSM parameter
 - Direct heavy MSSM Higgs mass scale determination:
 - investigate channel $e^+e^- \rightarrow \nu\bar{\nu}H$ (in m_h^{\max} scenario)
 - loop corrections modify decoupling behavior
 - ⇒ large enhancement of reach beyond $M_A \lesssim \sqrt{s}/2$ possible